Calibration and modification of impedance probe for near surface soil moisture measurements

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[1]Department of Plant and Soil Sciences, Alabama A&M University, Normal, AL 35762, USA (e-mail: ttsegaye@aamu.edu); [2]USDA-ARS, Beltsville, MD 20705, USA; [3]USDA-ARS, Mississippi State, MS 39762, USA. *Received 16 September 2003, accepted 22 January 2004.*

Tsegaye, T. D., Tadesse, W., Coleman, T. L., Jackson, T. J. and Tewolde, H. 2004. **Calibration and modification of impedance probe for near surface soil moisture measurements**. Can. J. Soil Sci. **84**: 237–243. A reliable and low cost sensor that can measure soil moisture at or near the soil surface is currently not available. The objectives of this study were: (i) to evaluate the possibility of modifying an impedance probe (IP) to measure soil moisture content at a very shallow depth (2–5 cm); and (ii) to compare the soil moisture values obtained using the IP to the values obtained using the traditional gravimetric method. The research was conducted at the Winfred A. Thomas Agricultural Research Station (WTARS) Hazel Green, Alabama. The standard IP that is capable of measuring soil moisture content at 6-cm soil depth was modified to measure soil moisture at 2-, 3-, and 5-cm depths. Using a site and depth-specific calibration technique it provided results that were comparable to the values that were obtained following the traditional gravimetric water content determination protocol. We found that the instrument was very sensitive to changes in soil moisture content and has great potential as a replacement for the gravimetric technique. It allows repetitive measurements of soil moisture content at a very shallow depth with minimal soil disturbance. Furthermore, the instrument is particularly valuable for providing ground- truth soil moisture contents to validate remotely sensed data.

Key words: Soil moisture, remote sensing, impedance probe, ground-truth, validation

Tsegaye, T. D., Tadesse, W., Coleman, T. L., Jackson, T. J. et Tewolde, G. 2004. **Étalonnage et modification de la sonde à impédance pour dosage de la teneur en eau à la surface du sol**. Can. J. Soil Sci. **84**: 237–243. Actuellement, il n'existe pas de sonde fiable ni bon marché permettant d'établir la quantité d'eau dans le sol près de la surface. La présente étude devait : i) établir si on peut modifier une sonde à impédance (SI) afin de mesurer la teneur en eau à très faible profondeur (de 2 à 5 cm) et ii) comparer les valeurs de la sonde à celles recueillies de la manière habituelle (gravimétrie). Les essais se sont déroulés à la station de recherche agricole Winfred A. Thomas de Hazel Green (Alabama). La SI standard, capable de mesurer la teneur en eau du sol à 6 cm de profondeur, a été modifiée pour effectuer ce relevé à 2, à 3 et à 5 cm. L'application d'une technique d'étalonnage spécifique au site et à la profondeur donne des résultats comparables à ceux obtenus avec le protocole usuel faisant appel à la gravimétrie. Les auteurs ont constaté que l'appareil est très sensible aux variations de la concentration d'eau et pourrait remplacer efficacement la technique gravimétrique. La sonde autorise les relevés répétitifs de la teneur en eau à une très faible profondeur sans grande perturbation du sol. Par ailleurs, l'appareil s'avère fort utile pour valider les données obtenues par télédétection par vérification de la concentration d'eau réelle au sol.

Mots clés: Teneur en eau du sol, télédétection, sonde à impédance, vérification au sol, validation

Soil moisture measurement at or near the soil surface with minimum sampling and measurement errors is important to relate ground-based measurements to remotely sensed data. Soil moisture is a key element in agricultural, hydrological, and climatic systems. The spatial and temporal variability of soil moisture directly affects plant growth and crop yields. They also impact the water and energy cycles of the earth. In essence soil moisture directly impacts evapotranspiration, infiltration and runoff, and it plays an important role in regional- to global-scale general circulation models (GCM) because it controls precipitation and evapotranspiration. Thus, increasing the understanding and estimation of the space-time structure of soil moisture is essential to improve the predictability of soil moisture (Engman et al. 1989).

A reliable estimate of soil moisture content at the surface and the manner that it is influenced by surface and atmospheric characteristics are of interest to agronomic, climatic, and hydrological studies. Remotely sensed data in conjunction with in situ soil moisture measurements (Tsegaye et al. 1997) can be valuable tools to estimate soil moisture over a wide range of spatial and temporal scales (Tsegaye et al. 1998). However, there are several issues that need to be addressed before making inferences about soil moisture variability using remotely sensed data. A very good link between the biophysical parameters needed to estimate soil moisture and the observational ones obtained by the remote sensing should be established.

The quantity of soil moisture present at or near the soil surface affects processes such as microbial activity, surface

Abbreviations: **GSM**, gravimetric soil moisture content; **IP**, impedance probe; **VWC**, volumetric water content

Fig. 1. The modified version of the impedance probes connected to the hand-held reader unit.

heat fluxes and energy exchange. Atmospheric and hydrologic models require surface soil moisture content as a boundary condition in order to estimate surface and subsurface movement of water. The daily measurement of surface soil moisture content on a large area can be tedious and difficult. One of the most promising noninvasive techniques for monitoring near surface soil moisture content over large areas is microwave remote sensing (Jackson et al. 1982; Schmugge et al. 1980, 1996). However, as the spatial scale of a satellite footprint and temporal frequency of sensor coverage increases in future missions, the problem of validating soil moisture imagery derived from microwave sensors is compounded. This is due in large part to the difficulties associated with collecting representative ground truth data sets given the increasing size of satellite footprints and the high degree of spatial-temporal moisture content variability within these footprints.

The gravimetric method involves removing a known volume of soil sample from the field and determining the mass of water content in relation to the mass of the dry soil. Although the use of this technique usually ensures accurate measurements, it also has a number of disadvantages. For example, a repeated measurement at exactly the same location is impossible due to the destructive nature of the methodology. In addition, laboratory equipment, sampling tools, and over 24 h of drying time are also required. Eventually, measurements will become inaccurate because of field variability from one site to another. Gravimetric soil moisture content (GSM) is the de facto standard for verification of remote sensing and all other soil moisture field experiments. Because GSM is a destructive technique, one does not directly sample the footprint area during a prolonged experiment. Thus, one must understand the variability of soil moisture within the test bed to understand the errors that might be associated with GSM outside the footprint area. The objective of this research was to evaluate the possibility of modifying an impedance probe (IP) to measure soil moisture content at a very shallow depth (2-5 cm); and (ii) to compare the soil moisture values obtained using the IP to the values obtained using the traditional gravimetric method.

MATERIALS AND METHODS

Sensor Description

Surface volumetric soil moisture was measured with an IP sensor. The IP is a manually operated instrument manufactured by Delta-T Devices, Ltd., Cambridge, England, and distributed in the United States by Dynamax, Inc., Houston, TX. The IP has a smaller, cylindrical design and requires a

Table 1. Selected physical and chemical properties for the Decatur, Bama, and Quincy soils

Soil properties	Decatur	Soil types Bama	Quincy
pH	5.54	5.19	6.29
Organic C (%)	1.37	1.73	0.69
Particle density (g cm^{-3})	2.64	2.75	2.84
Particle size (%)			
Clay	33	11	11
Silt	54	17	12
Sand	13	72	77
Predominant clay	Kaolinite	Kaolinite	Smectite
Porosity (%)			
Unpacked	61.74	55.27	49.65
Packed	51.52	44.00	39.79
CEC (cmol kg^{-1})	4.42	6.97	5.99
Specific surface area (m^2 g^{-1})	51.88	19.52	54.11

5-cm-diameter access hole in the soil for obtaining soil moisture readings at depths beyond the 6-cm soil depth. The IP also has four 6-cm stainless steel rods that are inserted vertically into the soil (Fig. 1). The instrument was connected to a hand-held reader, which delivers the electrical pulse, detects the return signal and converts the period to voltage (V) between 0 and 1 V for dry to saturated conditions (Delta-T Devices, Ltd., Cambridge, England). In the field, observed voltages were recorded by hand. The readout from the IP was later converted to volumetric water content using a site-specific calibration curve. Using the IP instrument, it is easy to make rapid, reliable, accurate volumetric soil moisture measurements under a variety of difficult and extreme conditions. It is necessary to provide 5–15 V DC at about 20 mA. During this experiment, we felt the connection from the probe to the hand held reader could be made more robust to withstand constant connecting and disconnecting.

The research was conducted at the Winfred A. Thomas Agricultural Research Station (WTARS) near Hazel Green, Alabama. The IP instrument was evaluated on a Decatur silt loam soil in the field and in the greenhouse using three soil types collected from three locations in Alabama. The soils used in the laboratory were Bama fine sandy loam (Fine-loamy, siliceous, subactive, thermic Typic Paleudults), Decatur silt loam (Fine, kaolinitic, thermic Rhodic Paleudults), and Quincy fine sand-grassland (Mixed, mesic Xeric Torripsamments). The 6-cm-long IP, which is currently available and sold on the market by Dynamax, Inc., was modified in our laboratory to take near surface soil moisture measurements at 2-, 3-, and 5-cm depths. Probe length was modified by inserting 4-, 3-, and 1-cm closed PVC tubes filled with cell foam to the 6-cm IP probe in order to have the required 2-, 3-, and 5-cm probe length to measure soil moisture contents. The cell foam was used to fill the void space within the PVC tube. After taking the IP voltage readings, the probe was carefully removed with minimal soil disturbance. Immediately, known volumes of soil samples were collected using two core-sampling techniques to determine the gravimetric water content of the soil.

Greenhouse Study

A greenhouse study was conducted on the three soil types. The soils were uniformly packed in a 1-m^3 box based on their predetermined bulk density (Table 1). The soil beds were uniformly wetted and brought to saturation by sprinkling water on the surface. After 24 h of equilibration, the four probes were inserted vertically and voltage readings were recorded. The greenhouse experiment remained in operation until voltage readings were collected on several occasions in order to evaluate the performance of the modified IP under a wide range of soil moisture conditions.

Soil Sampling

Both a scoop and a soil core sampler were used to determine the volumetric water content (VWC) of the soil. At the beginning of the experiment we found the soil core sampler to be more accurate as compared to the scoop sampler since the core sampler has less sampling error in providing relatively exact soil volume as compared to the scoop sampler; therefore, soil moisture content values obtained following the core sampling protocol were used to develop the calibration curves and to examine the performance of the modified IP.

Scoop Soil Sampling Procedure

The scoop soil samplers were reproduced in a local metal fabrication shop in Huntsville, Alabama. Each sampler collects approximately 72, 108, 125, and 216 cm^3 of soil from 2-, 3-, 5-, and 6-cm soil depths, respectively.

Sampling steps using the scoop sampler

1. Prepare the surface with minimal soil disturbance by the removal of vegetation and litter.
2. Insert all four IPs into the ground, record the voltage (V) output and remove the IPs with minimum soil disturbance.
3. Use a large spatula (6 cm) to cut a vertical face at least 8 cm deep.
4. Push the scoop sampler into this vertical face. The wings of the scoop should rest on the soil surface.
5. Use the large spatula to cut a vertical face on the front edge of the scoop.
6. Place sample in a pre-weighed and labeled soil moisture can; a small spatula aids extraction.
7. Immediately record the wet weight of the sample and the can.
8. Transfer the sample into a preheated oven at 105–108°C for over 24 h.
9. Record the oven-dry weight.
10. Determine mass wetness using the relationship (wet wt. – dry wt.)/dry wt.
11. Calculate dry bulk density, bulk density = oven dry mass soil/total volume.
12. Finally, calculate the VWC of the soil using the relationship VWC = mass wetness × bulk density.

Soil Core Sampler Procedure

Soil Moisture Equipment Corp. manufactured the soil core samplers. The soil core sampler was designed to collect soil core samples of a known volume with minimal disturbance and compaction. To get the required depth of soil sampling,

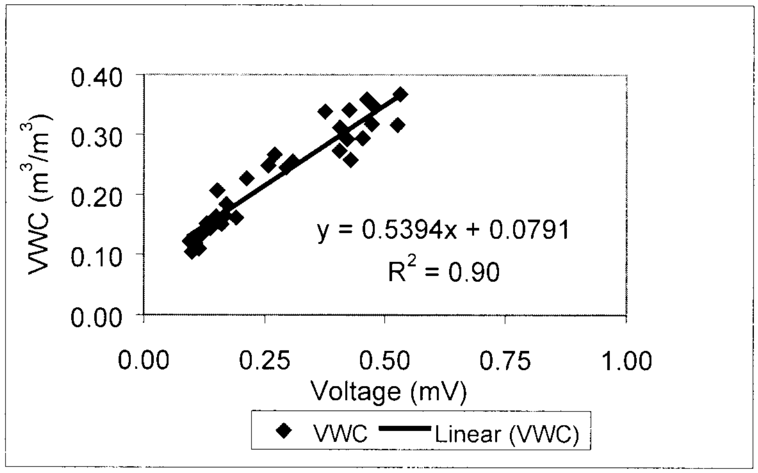

Fig. 2. Calibration curve for 2-cm soil depth.

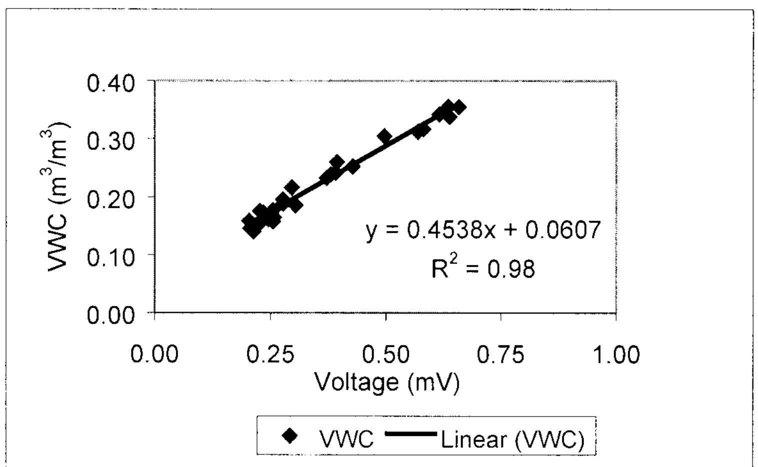

Fig. 3. Calibration curve for 3-cm soil depth.

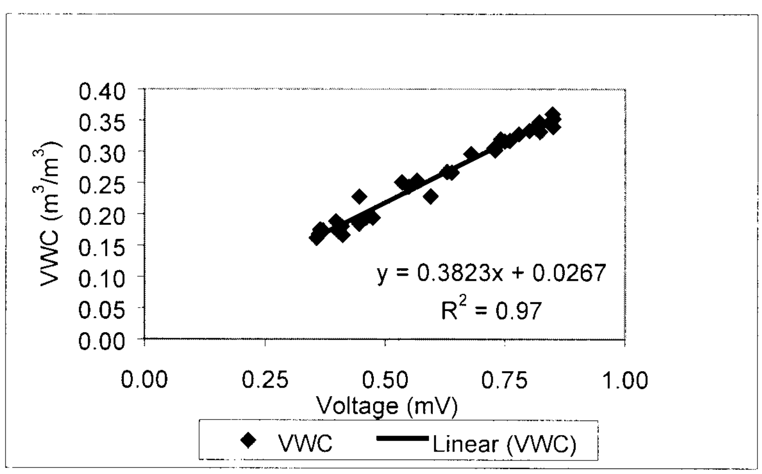

Fig. 4. Calibration curve for 5-cm soil depth.

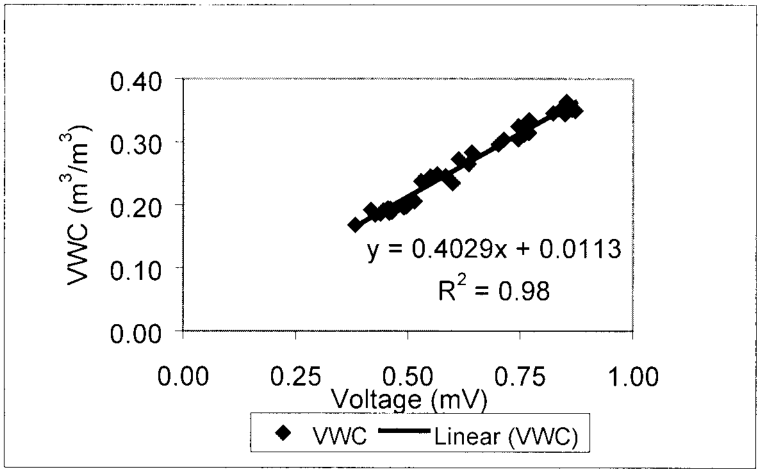

Fig. 5. Calibration curve for 6-cm soil depth.

Table 2. Mean comparisons of measured volumetric water content (VWC) values using the impedance probe (IP) and gravimetric technique (GSM)

Measurement technique	Depth (cm)	Sampling periods 1	2[z]	3	4
IP	2	0.303*a*	0.343*a*	0.243*a*	0.139*a*
GSM	2	0.293*a*	0.263*b*	0.243*a*	0.126*a*
IP	3	0.320*a*	0.348*a*	0.241*a*	0.166*a*
GSM	3	0.313*a*	0.345*a*	0.241*a*	0.164*a*
IP	5	0.317*a*	0.350*a*	0.249*a*	0.184*a*
GSM	5	0.310*a*	0.345*a*	0.249*a*	0.171*a*
IP	6	0.305*a*	0.352*a*	0.257*a*	0.196*a*
GSM	6	0.305*a*	0.350*a*	0.257*a*	0.184*a*

[z]Soil sampling and IP measurements were taken a day after a rainfall event.
a Means within a sampling period and soil depth followed by the same letter are not significantly different ($P \leq 0.05$).

using a combination of one or more rings having different lengths i.e., 6, 5, 4, 3, 2, and 1 cm, undisturbed soil core samples were collected from four soil depths, i.e., 2, 3, 5, and 6 cm. Soil core samples from each soil depth were collected by accommodating the sensor's primary zone of influence, which is ≈ 6-cm in diameter.

Sampling steps using a soil core sampler

1. Prepare the surface with minimal soil disturbance by the removal of vegetation and litter.
2. Insert the IPs into the ground, record voltage (V) outputs, and remove the IPs with minimal soil disturbance.
3. Hammer the soil core sampler to the depth of interest. At this stage, care should be taken to avoid or minimize soil compaction.
4. Remove the soil around the core sampler, tilt the sampler to one side and remove it.
5. Take out the rings that contain the soil inside the sampler using a wood block as a support by inverting the sampler upside down.
6. Trim or remove excess soil from the bottom part of the ring using a knife or a spatula.
7. Immediately transfer the soil samples into pre-weighed soil moisture cans.
8. Record the wet weight of the soil, including the can weight.
9. Transfer the sample into a preheated oven at 105–108°C for over 24 h.
10. Record the oven-dry weight.
11. Determine the mass wetness using the relationship, (wet wt. – dry wt.)/dry wt.
12. Calculate dry bulk density, bulk density = oven dry mass soil/total volume.
13. Finally, calculate the VWC of the soil using the relationship, VWC = mass wetness × bulk density.

Calibration Procedures

If one wants to use an IP and obtain an accurate measurement of soil water content, it is necessary to have a site- and depth-specific calibration due to the site-specific variability of soil properties as well as electromagnetic effects of soil materials. If the primary purpose of the measurement is to account for relative differences in soil moisture content, then the factory calibration can be used for the 6-cm probe length, knowing that there is some error associated with the calibration curve. The standard reference for calibrating soil moisture measuring instruments is the gravimetric technique, with soil samples collected within the sensor's primary zone of influence.

Table 3. Mean comparisons for volumetric water content (VWC) values determined using the impedance probe (IP) at different depths for Decatur, Bama, and Quincy soils

		VWC ($m^3\ m^{-3}$)		
		Soil type		
Sampling date	Soil probe length (cm)	Decatur	Bama	Quincy
1	2	0.268*a*	0.242*b*	0.197*c*
	3	0.303*a*	0.286*b*	0.239*c*
	5	0.362*a*	0.333*b*	0.290*c*
	6	0.366*a*	0.321*b*	0.301*c*
2	2	0.256*a*	0.246*b*	0.185*c*
	3	0.300*a*	0.258*b*	0.216*c*
	5	0.355*a*	0.310*b*	0.269*c*
	6	0.357*a*	0.308*b*	0.270*c*
3	2	0.233*a*	0.139*c*	0.164*b*
	3	0.280*a*	0.159*c*	0.186*b*
	5	0.319*a*	0.211*b*	0.214*b*
	6	0.326*a*	0.240*b*	0.238*b*

a–c Means within a sampling period and soil depth followed by the same letter are not significantly different ($P \leq 0.05$).

Since random errors associated with IP measurements are much smaller than gravimetric sampling, great care must be taken to accurately determine the dry bulk density and gravimetric water content within the primary sensing volume of the IP. For this study we developed:

A Site- and Depth-specific Calibration Curve

1. Initially the soil was brought to near saturation.
2. Using each IP depth, voltage (V) readings were recorded and each one of the IP sensor was carefully removed with minimal soil disturbance.
3. Immediately, gravimetric soil samples were collected using a soil core sampler from the same location where the probe reading was recorded to determine the VWC for each specific soil depth.
4. Step (2) and (3) were repeated as the soil dried to get a range of voltage (V) readings and VWC ($m^3\ m^{-3}$) values.
5. A scatter plot was developed using Voltage (V) and VWC ($m^3\ m^{-3}$).
6. The equation that fits best to the data was determined.

RESULTS AND DISCUSSION

Depth-specific field calibration curves for 2-, 3-, 5-, and 6-cm probe lengths were developed using field-collected data under a bare soil condition (Figs. 3–5). The calibration curve provided for the 6-cm probe by the manufacturer to relate the IP output and soil moisture content is a non-linear curve. In this study, linear regression equations were developed to define the relationship between the voltage and VWC for all probe length. The R^2 for the calibration curves ranged from 0.90 to 0.98. The slope of each calibration curve is different as shown on the graphs i.e., the percent slope decreased as the probe length increased.

The VWC values obtained using the gravimetric technique (using a soil core sampler) and the IP instruments are given in Table 2. The mean volumetric water content values determined by the gravimetric technique (GSM) were, in general, identical to the IP values (IP) obtained using the site-specific calibration curve for each depth. We repeatedly tested the performance of the IP under two extreme conditions, i.e., extremely wet and dry soil conditions. The instrument provided a voltage reading close to 0.9–1.00 V when the soil is nearly saturated and provide a voltage reading of 0.1–0.15 V for extreme dry soil conditions. Even though we were able to take measurements under extreme wet or dry conditions, we found that it is sometimes difficult to get a representative sample volume for the gravimetric technique under these two extreme soil conditions in the field. Except for the 2-cm probe length for sampling period 2, the measured values using the two measurement protocols were within a ± 3% range of each other (Table 2).

Volumetric water content values determined using an IP for the Decatur, Bama, and Quincy soils in the greenhouse study are given in Table 3. As shown in Table 1, all three soils have exhibited somewhat distinct features of soil physical and chemical properties. At the beginning of the greenhouse study, the soils were wetted uniformly in order to minimize the spatial variability of soil moisture content and minimize sampling and measurement errors. During the course of this greenhouse experiment, the spatial and temporal variations of soil water content distributions, in general, were detected (Table 3) for all soil types as the soil dried from sampling date 1 (wet) to date 3 (dry) conditions. The instrument detected the change in soil water content for all soil depth. Decatur soil, which has a high percent clay content, had higher water content as compared to both the Bama and Quincy soils, which have relatively low levels of clay. Variation in soil pH, soil texture, and organic matter content did not affect the IP performance to accurately detect the changes in soil moisture content over time. The instrument, in general, provided reproducible voltage readings for all probe depths over time as the soil dried.

SUMMARY AND CONCLUSION

The overall goal of this research was to find a simple, fast and effective method to measure near-surface soil moisture content, which, in turn, could assist researchers in the remote sensing discipline to validate remotely sensed data at local and regional-scale field experiments. The performance of the modified version of the IP in both the field and greenhouse experiments was very good and can meet such requirements. As long as one develops and uses depth- and a site- specific calibration curves, the instrument has great potential to detect changes in soil moisture content at 2-, 3-, and 5-cm soil depths. Furthermore, the instrument can also provide an estimation of near-surface soil moisture content within a 3% accuracy range to the values determined by the gravimetric technique.

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